

40 years of the Nobel prize in physics: then and now

R A Broglia

Dipartimento di Fisica, Università di Milano, Via Celoria 16, I-20133 Milano, Italy

The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

Abstract

The findings for which Aage Bohr and Ben R. Mottelson became co-winners of the 1975 Nobel prize in physics provided the basis for a comprehensive and operative answer to the central problem in the study of the nuclear structure, namely the identification of the appropriate concepts and degrees of freedom that are suitable for describing the phenomena encountered. To do so they produced a breathtaking unification of a number of well established concepts, namely liquid drop and shell models, elementary modes of excitation, superconductivity and quantum electrodynamics, resulting eventually in the paradigm of broken symmetry restoration to determine the nuclear collective variables (CV, elementary modes of excitation): violation of translation invariance by the mean field and by scattering states (single-particle motion), of rotational invariance in the variety of spaces, in particular in 3D- and in gauge-space, leading to surface vibrations and to quadrupole rotations, as well as to pairing vibrations and rotations, with associated emergent properties of generalized rigidity in these spaces, resulting from the coupling to single-particle degrees of freedom.¹

1 Foreword

The story starts in October 1974 where we, at the Institute, were waiting for the announcement of the Kungliga Vetenskapsakademien concerning the

¹Invited lecture delivered on December 14th, 2015 in occasion of the celebration by the Niels Bohr Archive of the 40th anniversary of Aage Bohr and Ben Mottelson co-sharing of the 1975 Nobel Prize in Physics, held in the historic Auditorium A of the Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark

Nobel Prize in physics. One was quite confident that this one was the year of Aage and Ben. However, the laureates of 1974 were Martin Ryle and Anthony Hewish, for their contributions to radio astrophysics² (aperture synthesis technique and discovery of pulsars respectively). We were taken aback. Some however, decided on short call to react strongly, asking the, at the time, resident of Carlsberg's æresbolig, Professor Bengt Strömgren to make the presentation of the candidates for 1975.

2 Then

We all know the way things went, and on December 14th, 2015 one celebrated within the scenario of the famous Auditorium A of the Institute of Theoretical Physics of the University of Copenhagen (now Niels Bohr Institute) the 40th anniversary of the Nobel Prize in nuclear physics; *"For the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of structure of the atomic nucleus based on this connection"*.

Within this context, let me quote the assessment made some years before (1972) by Phil Anderson concerning the work which is at the basis of the event of the present celebration: "It is fascinating ... that nuclear physicists (referring to A. Bohr and B.R. Mottelson, *Collective and individual-particle aspects of nuclear structure*, Mat. Fys. Medd. Dan. Vid. Selsk. **27**, no. 16 (1953)) stopped thinking of the nucleus as a featureless, symmetrical little ball and realized that ... it can become (american ,RAB) football-shaped or plate-shaped. *This has observable consequences in the reactions and excitation spectra* that are studied in nuclear physics ... this ... research ... is as fundamental in nature as many things one might so label" (P.W. Anderson, *More is different. Broken symmetry and the nature of the hierarchical structure of science*, Science **177**, 393 (1972); within this context see App. A). And again, almost 30 years later, describing the activity of the theoretical physicists in the sixties and early seventies: "... *the story of broken symmetry* ... is a heartening story of one of those rare periods when the fragmentation of theoretical physics into condensed-matter, nuclear and particle branches was temporarily healed and we were all consciously working together in ex-

²I recall that morning having met Aage at the library of the Institute, and having heard him commenting on some of the physical properties of pulsars.

ploring the many quantum consequences of the idea of broken symmetry” (P.W. Anderson, *A helping hand on elementary matters*, Nature, **405**, 736 (2000); see App. B).

I believe that the above texts accurately describe the *magic period* during which the basic concepts and some of the fundamental results which are at the basis of the 1975 Nobel prize in physics were developed at the Institute.

2.1 The press

The announcement of the Nobel prize by the Kungliga Vetenskabakademien took place on Friday, October 17, 1975. That Saturday, all newspapers carried the story. One of them (Aalborg Stiftende) with excerpts of an interview Aage had given to the press in his home in Hellerup³. To the journalist (Claus J. Deden) question ⁴ ”om hans arbejde ikke er en videreførelse af faderens arbejde. Det arbejde, Niels Bohr fik er Nobel-pris for i 1922” he answered (my translation): ”My father’s work cannot be compared with mine. His work was an epoch-making event within the whole development of physics. My work is a different and more modest contribution to this development. But one can correctly say, that my work carries on that of my father ... we have directly built further based on his work”.

The journalist then writes that Aage emphasized, during the whole interview, how he viewed the bestowal: ”One is talking about that all, the whole group of theoretical physicists at the Institute, have taken part in the work that is being recognized. Furthermore, one refers to an international collaboration. I cannot take all the honour for it”⁵.

³One is reminded of the fact that when the announcement came from Stockholm, Ben was in Bangkok in his way to China with a delegation from the Royal Danish Academy of Sciences and Letters. After his return to Copenhagen in November, Aage and Ben started coordinating and writing their Nobel lectures. I was call one day in early afternoon to Granhøjten 10, to act as sounding board and discuss specific points (Nuclear Field Theory with Ben, rotations, in particular pairing rotations with Aage). Aage sat at his desk, Ben, on the room contiguous to Aage’s studio, at a low coffee table on a big, four people sofa, with his ever smiling expression. I do not know exactly why but, these two geniuses of physics appeared to me at the moment, as the kind Professor and the bright student.

⁴”whether his work is not a continuation of his father’s work. The work, Niels Bohr got a Nobel prize for in 1922.”

⁵At this point I cannot avoid telling you how sad I am that Aage is not anymore among us. The best way I can remember him today, is by trying to imagine what his reaction would have been to my presentation. I could vividly see him smiling at each important statement, and mumbling something to himself. If you payed attention you could likely hear him saying: “yes but not quite...”. The depth of his thoughts, the accuracy, physical

2.2 Place and impact of the 1975 view of nuclear physics within the general developments

Let me remind you that this year (2015) we are also celebrating another 40 year recurrence. The publication of Vol. II of Nuclear Structure, the definitive treatise on the subject by Aage and Ben. The 1975 Nobel Prize in physics was, to a large extent, honoring the unified vision of nuclear physics contained in these two volumes. Anybody who has studied and used them, in particular Volume II with its 748 pages, realizes that this monumental work not only testifies to the deep vision Aage and Ben developed of the atomic nucleus, but the inspiration they provided through the years to so many practitioners, theorists and experimentalists alike, to explore new areas and carry out independent cutting edge research. Within this context Aage's words to the journalist concerning "a common enterprise" is not only an expression of dignity of a unique team of scientists, but a true description of an heroic scientific achievement of which they were not only the central figures, but also the inspiring force and the living intuition of this new research field.

Returning to the first part of Aage's press interview, while nobody will be able to disagree with his judgment concerning the significance of Niels Bohr's work compared to that of him done in collaboration with Ben, I take issue at the fact that they have just built on the top of it. *They have changed the nuclear paradigm in an essential way*, providing an unification of short, mean free path, local equilibrium models (Niels Bohr and Fritz Kalckar, liquid drop, Niels Bohr, compound nucleus), with a long mean free path, independent particle motion picture, to be found at the basis of the shell model of Marie Goeppert Mayer and Hans Jensen⁶. In a nutshell, the particle-vibration cou-

accuracy, of his intuitions, made of each single issue an important piece of the whole mosaic. A never ceasing probing of the correctness of the ideas and predictions, which we sorely miss. The best antidote to it? To study his monumental opus written together with Ben when confronted with new challenges. There are still many nuggets to be extracted from this gold mine.

⁶Likely, the most illustrative way to express this unification sounds (quoting Ben Motelson): "It is a rather unfortunate perversity of the popular terminology that regards this collective field as in some sense an antithesis to the nuclear collective effects. B.R. Motelson, in Proc. of the "E. Fermi" Int. School of Physics, Course XV, *Nuclear spectroscopy*, G. Racah ed., Academic Press, New York (1962), p.44. To illustrate this point to my fourth year students at the University of Milan, I used to propose the following analogy: "independent-particle motion in nuclei is like to drive my car from Via Celoria 16 (address of the Department of Physics) to the Duomo and back without finding a single red light,

pling (PVC) is at the basis of the processes required by quantum mechanics concerning the evolution of systems made out of fermions and bosons (Fig.1). Namely: (a) vacuum self-energy (Heisenberg's indeterminacy- and Born's commutation- relations), (b) single-particle self-energy (right, Pauli principle, Lamb shift-like diagram⁷; left, time ordering). These processes allow, for nucleons moving several MeV away from the Fermi energy, to undergo transitions (damping) between independent-particle motion with a long mean free path towards a regime of short mean free path (as compared to nuclear dimensions), through the variety of doorway states. That is, states containing an odd number of fermions and any number of collective vibrations (bosons). Scattering (PVC) vertices and their consequences cannot be avoided, not even within RPA (Bohm and Pines, see diagram (c) Fig. 1), in keeping with

nor another vehicle in my way". Unarguably, the outcome of a rather coordinated city street ballet.

⁷A consequence of quantum mechanics at large, and of quantum field theories in particular is that the vacuum is not a simple entity. It can be virtually excited (see 1(a) and interpret λ as the photon and the upward (downward) going particle as the electron (positron)). To the question of Rabi of whether the polarization of the vacuum could be measured (A. Pais, *The genius of Science*, Oxford (2000)), Lamb gave a quantitative answer, both experimentally and theoretically (W. E. Lamb Jr. and R. C. Retherford, *Phys. Rev.* **72**, 241 (1947), N. M. Kroll and W. E. Lamb Jr. **75**, 388 (1949)). In the nuclear case Fig. 1(a) represents the ground state fluctuations while graphs (b) result by adding one nucleon to the system. The second order process associated with antisymmetrization between the single nucleon considered explicitly and the nucleons out of which the vibrations are built, as well as the symmetrization between nuclear vibrations renormalizing the nucleons and eventually excited by external fields were first introduced in B. R. Mottelson (*Proc. of the Int. Conf. on Nuclear Structure*, Suppl. to *J. Phys. Soc. Japan*, **24**, 87 (1968); see also A. Bohr and B. R. Mottelson *Nuclear Structure Vol II* (1975), p. 427, Fig. 6.10; see also D. R. Bès, *Special Physic Scripta Edition -40 year anniversary- Nobel Prize in Physics 1975*). Within this context one is reminded of the fact that Aage attended the Pocono conference (30/3-1/4, 1948) where Feynman presented his version of QED (after Schwinger). In explaining his formalism, he pointed out that one did not need to worry about the Pauli principle in intermediate states, as there were diagrams which properly took care of it. Likely, the fact that to Teller's question: "You mean that helium can have three electrons in the s -state for a little while?" Feynman gave an affirmative answer with the ensuing chaos (see Schweber *QED Princeton Univ. Press* 1994, p. 442) arguably could also have been at the basis of Ben Mottelson contribution to the Tokyo conference, also with the input of Aage. "Major parts of the present report have been taken from a monograph which is in preparation jointly with Professor A. Bohr" reads in the acknowledgment of Ben's Tokyo contribution (appeared also as No. 265 of NORDITA publications).

Pauli principle and with the fact that both even or odd number of fermions can be present in the systems under study.

The work of Aage and Ben was also instrumental to establish connections between nuclear structure with many-body and field theory physics: Elementary modes of excitation (Lev Landau); Spontaneous symmetry breaking (BCS, Josephson, Phil Anderson); Field theories (Richard Feynman).

The validity of the ensuing unification in terms of the symmetry breaking restoration paradigm⁸ and resulting elementary modes of excitation and couplings, which looks short of unbelievable at first sight, is likely to be deeply rooted in the fact that many, if not most, high-dimensional models, as well as real processes, are "sloppy", as a consequence of the emergence of variables of greatest interest⁹

3 Now

The relevance for today's nuclear physics research of Aage's and Ben's contributions recognized by the Swedish Academy can be exemplified by quoting from their Nobel lectures. In p. 370 of Rev. Mod. Phys. **48** (1976), Aage writes: "The condensates in superfluid systems involve a deformation of the field that creates the condensed bosons or fermion pairs. Thus the process of addition or removal of a correlated pair of electrons from a superconductor (as in a Josephson junction) or of a nucleon pair from a superfluid nucleus constitutes a rotational mode in which particle number plays the role of angular momentum (Anderson, 1966). Such pair rotational spectra, involving a family of states in different nuclei, appear as a prominent feature in the study of two-particle transfer processes (Middleton and Pullen, 1964;

⁸It is of notice that the paradigm of broken symmetry restoration which most physically and economically allows one to introduce and determine the elementary modes of excitation, is not to be found in the 1953 paper, nor for that sake in A. Bohr's contribution to the 1964 Paris Congress (A. Bohr, Comptes Rendus du Congrès International de Physique Nucleaire, Vol. I, I.P. Gugenberg ed., Editions du Centre National de la Recherche Scientifique, Paris, (1964), p.487), while it is embodied in the discussion of pairing rotations and vibrations of 1968 supplied by the corresponding references (A. Bohr, *Pair correlations and double transfer reactions*, Nuclear structure, Dubna Symposium, IAEA (1968) p.179).

⁹Cf. M. Buchanan, *Wheat from the chaff*, Nature Physics, **11**, 286 (2015); M.K. Transtrum et al., J. Chem. Phys. **143** 010901 (2015).

see also Broglia et al, 1973)¹⁰. The gauge space is often felt as an abstract construction but, in the particle-transfer process¹¹ it is experienced in a very real manner”. While the sequence of levels displayed in Fig. 2 have been known for quite some time, the account of the absolute two-nucleon transfer differential cross section is of new date¹², making Cooper pair transfer a quantitative probe of pairing correlations in nuclei, carried out in terms of absolute cross sections and not relative ones as done before. A result which took short of forty years to be accomplished and involved an important fraction of the nuclear physics community (see Fig. 10 of Potel et al. (2013)). Paramount in this development was the role played by Claus Riedel at the beginning and that of Aage Winther and Ben Bayman throughout.

Let me now quote from Ben’s Nobel lecture (Rev. Mod. Phys. **48** (1976), see p. 382): ”As illustrated by these examples, it appears that the nuclear field theory based upon the particle-vibration coupling provides a systematic method for treating the old problems of the overcompleteness of the degrees of freedom, as well as those arising from the identity of the particles appearing explicitly and the particles participating in the collective motion (Bes et al., 1974; Bohr and Mottelson, 1975)¹³. This development is one of the active frontiers in the current exploration of nuclear dynamics” (see App. C). Fig. 3, which displays an example of NFT at work today¹⁴, provides a complete characterization of ^{118,119,120,121,122}Sn, and testifies to the actuality of Ben’s words. This result has again taken many decades to be obtained and has

¹⁰P. W. Anderson, Rev. Mod. Phys. **38**, 298 (1966); R. Middleton et al., Nucl.Phys. **51**, 77 (1964); R. A. Broglia et al., Adv. Nucl. Phys. **6**, 287 (1973).

¹¹The fingerprint of spontaneous symmetry breaking in finite, many-body systems, is the presence of rotational bands associated with symmetry restoration. To qualify as a rotational band, a set of levels must display enhanced transition probabilities (absolute cross sections), associated with the operator having a non-vanishing value in the (degenerate) ground state (order parameter). In the present case (pairing rotational bands), of the two-nucleon transfer operator. In other words, cross talk (absolute transfer cross sections) between a member of a pairing rotational band and states not belonging to it, should be much weaker than that between members of the band. It could be argued that also important for the characterization of a pairing rotational band is the parabolic dependence of the energy with particle number. True, but many non-specific effects can modify this dependence, without altering the gauge kinship (common intrinsic state).

¹²Potel et al. Rep. Prog. Phys. **76** 106301 (2013)

¹³D. R. Bes et al., Phys. Lett. B **52**, 253 (1974); A. Bohr and B. R. Mottelson, *Nuclear structure*, Vol. II, Benjamin, Reading (1975)

¹⁴A. Idini et al., Phys. Rev. C **92**, 031304(R) (2015)

involved an even wider number of contributing groups and practitioners. Among them one has to mention that of Pier Francesco Bortignon and the towering one of Daniel R. Bes.

Within this context, a textbook example of the fact that shell and liquid drop models are to be treated on equal footing, and eventually melt together, in the description of the nuclear structure, is provided by parity inversion in ${}^3_3\text{Li}$. Due to processes like those shown in Fig. 1(b), the level sequence $0p_{1/2}, 1s_{1/2}$ is inverted, the magic number $N=8$ melting away to lead to $N=6$ as new magic number¹⁵. In other words, self-energy effects are, as large, or even larger, than mean field effects in this exotic halo nucleus. Furthermore, the binding of the halo Cooper pair to the closed shell system (core ${}^9_3\text{Li}_6$) is essentially due to the induced pairing v_p^{ind} arising from the exchange of collective vibration between the two neutrons, the contribution of the strong nucleon-nucleon bare interaction v_p^{bare} to the Cooper pair binding being, in the present case, quite small. Such a possibility ($v_p^{ind} > v_p^{bare}$), had been already envisaged¹⁶ in Vol. II (cf. last paragraph in Sect. 6-5f, p. 432).

If there was need for any further documentation of the soundness of the Nobel Committee 1975 decision, one can refer to the consequences the paper by A. Bohr, B.R. Mottelson and D. Pines (A. Bohr *et al*, Phys. Rev. **110**,

¹⁵F. Barranco *et al*, Eur. Phys. J. A **11**, 385 (2001).

¹⁶In spite of this, Ben was rather negative concerning the whole issue of the induced pairing interaction in nuclei, arguing that most of the associated effects, were to be included in the polarization of the mean field, an understanding which is to be found at the basis of the pairing plus quadrupole (1959) Bohr and Mottelson model, according to which the long range part of the nuclear interaction is responsible for the creation of the average field, the short range part leading mainly to pairing correlations. Be as it may, the paper Barranco *et al* (2001) (footnote 15), originally submitted to Physical Review Letters, was rejected by the referee who not customary signed his report: Ben R. Mottelson. The predictions of the paper in question were eventually confirmed and provided, for the first time, evidence for phonon mediated pairing in nuclei (Tanihata *et al*, Phys. Rev. Lett. **100**, 192502 (2008); cf also Potel *et al*, Phys. Rev. Lett. **105**, 172502 (2010)). Arguably, the above story just tells one simple thing. If you are convinced of your ideas and results, just publish them. There is a delicious anecdote related to the referee report. In our answer to it, we appended a four pages long discussion where many of the consequences of the interweaving of single-particle and collective vibrations were derived in detail, within the framework of a simplified model. Our referee was very happy with it, and suggested to use it as appendix to our Phys. Rev. Lett., letter which already was slightly longer than the four allowed pages (the appendix was eventually published in F. Barranco *et al*. Phys. Rev. C **72**, 0543149 (2005)).

936 (1958)), introducing BCS pairing in nuclear physics¹⁷ has had over the years, by referring to the contributions collected in the 670 pages volume *Fifty years of nuclear BCS*.¹⁸

4 Conclusions

The unification of single-particle and collective motion which is at the basis of the ground-breaking contribution Aage Bohr and Ben R. Mottelson made to nuclear physics inspired and helped in a major way at developing the paradigm of broken symmetry restoration, and the physical tools to implement structure calculations in terms of the particle-vibration coupling mechanism (Feynman diagrams). Going beyond the harmonic approximation through scattering vertices, it allows for a systematic description of anharmonic effects and (doorway) damping. These major scientific breakthroughs were properly recognized by the Nobel committee in 1975.

Volume II of their treatise on Nuclear Structure is certainly no easy reading, in keeping with the fact that aside from containing the material describing the above mentioned phenomena and their implementation in concrete cases, it also provides a comprehensive account of the contributions of extensive NBI and international collaborations, and the basis to compare the theoretical physical results with the experimental findings obtained making use of nuclear reactions and decay processes. The fact that a three volume project became, in the end, a two volume one did not help on easiness of reading. Nonetheless, practitioners of other fields of physics, like condensed matter, cannot complain, neither explain that their knowledge of nuclear physics is limited at best, because nuclear physicists express themselves in a complicated language¹⁹. Unless physical insight and sheer unrelenting use

¹⁷Pairing in nuclei have been introduced in nuclear physics three times. The first two in terms of energy arguments and thus not exactly specific ones (enhanced stability of even-even systems compared to odd-even, even-odd, odd-odd (see e.g. W: Heisenberg *Die Physik der atomkerne* Friedr. Vieweg and Sohn de Bramschweig (Berlin) 1943); presence of a gap in the low-energy spectrum of deformed nuclei, Bohr, Mottelson and Pines (1958)). The third time in terms of the specific probe, namely two-nucleon transfer reactions (S. Yoshida, *Nucl. Phys.* **33**, 685 (1962), A. Bohr, Paris congress, see footnote 8).

¹⁸*Fifty years of nuclear BCS*, R.A. Broglia and V. Zelevinsky eds., World Scientific, Singapore (2013).

¹⁹Within this context one can agree that the language of nuclear field theory and of its

of physical intuition²⁰ can be deemed too trying. Here (volumes I and II) you find fermion superconductivity and Josephson pair tunneling and its particularization to finite systems and its extension to neutron (star) matter (pulsars). Furthermore spontaneous breaking of symmetries and associated Goldstone modes²¹, let alone all the elements, coupling constants and numerical factors to calculate, predict and analyze observables, within the remarkable femtoworld of the atomic nucleus.

Discussions with Gregory Potel, Francisco Barranco, Enrico Viguzzi, and Andrea Idini concerning a number of "now" subjects are acknowledged. A similar acknowledgment is extended to Pier Francesco Bortignon, also concerning a number of "then" subjects.

applications as developed by Aage, Ben and collaborators, was particularly original and for sure non-standard (see, e.g., the review of G. Breit and G. E. Brown of Volume II of Nuclear Structure, *Physics Today*, March 1977 pp. 59–62). This is in fact, one of the main challenges awaiting to be met. Namely, that of establishing a direct connection of the physics which is at the basis of Nuclear Structure Volume I and II, and thus of the 1975 Nobel prize in physics, with the theory of many-body physics and of effective field theories, heavily used by the physics community. The eventual outcome could prove momentous not only for present-day nuclear research, but also for finite many-body physics at large.

²⁰Quoting: "A priori one would believe that the easiest thing is to communicate simple concepts and phenomenology. This is totally wrong. Students are accustomed to mathematics, and the thing that they understand are mathematical models (JRS)", and : "On the other hand, people have to grow up (PWA)". From a discussion with Bob Schrieffer (JRS) and Phil Anderson (PWA) which took place in the first half of July 1987, at the shadow of the giant magnolia of Villa Monastero, Varenna, Como Lake (see R.A. Broglia and J.R. Schrieffer, eds., International School of Physics "Enrico Fermi", Frontiers and Borderlines in many-particle physics, Course CIV, North Holland, Amsterdam (1988)).

²¹Quoting from Aage's Nobel lecture "...the very occurrence of collective rotational degrees of freedom may be said to originate in a breaking of rotational invariance, which introduces a "deformation" that makes it possible to specify an orientation of the system. Rotation represents the collective mode associated with such a spontaneous symmetry breaking (Goldstone boson)". Discussing with Aage when applying these concepts to the treatment of pairing rotational bands (R. A. Broglia *et al* *Phys. Rep.* **335**, 1 (2000)), I remarked that the energy of the corresponding Goldstone mode should approach zero linearly as $N \rightarrow 0$, while the energy of the members of a pairing rotational band are quadratic in N . "True, but in fact one has to calculate this energy in the laboratory system, where one can measure it. For this purpose one should add the Coriolis-like term, linear in N ". That simple.

Appendix A. Good physics and reductionism

Let us quote from Leon Cooper's contribution to the volume **BCS: 50 Years** ²²: "It has become fashionable ... to assert .. that once gauge symmetry is broken the properties of superconductors follow ... with no need to inquire into the mechanism by which the symmetry is broken. This is not ... true, since broken gauge symmetry might lead to molecule-like pairs and a Bose-Einstein rather than BCS condensation ... in 1957, we were aware that what is now called broken gauge symmetry would, under some circumstances (an energy gap or an order parameter), lead to many of the qualitative features of superconductivity .. the major problem was to show how an energy gap, an order parameter or "condensation in momentum space" could come about ... to show ...how the gauge-invariant symmetry of the Lagrangian could be spontaneously broken due to interactions which were themselves gauge invariant" ..

Let us now go to the last contribution , namely that of Steven Weinberg (p.559). To do so, we have to browse through p. 85 where among other things, small "technical details"²³ concerning superconductivity in metals (namely electron-phonon coupling), are discussed by David Pines.

Quoting from Weinberg: " Most of us do elementary particle physics ... because we are pursuing a reductionist vision... I think that the single most important thing accomplished by ... (BCS) was to show that superconductivity is *not* part of the reductionist frontier ... (but) .. nothing more than a footling small interaction between electrons and lattice vibrations ... All of the dramatic exact properties of superconductors ... follow from the assumption that electromagnetic gauge invariance is broken ... with no need to inquire into the mechanism by which the symmetry is broken .. their (BCS, 1957) attention was focused on the details of the dynamics rather than the symmetry breaking".

²²L. N. Cooper, BCS: 50 Years, eds. L.N. Cooper and D. Feldman, World Scientific, Singapore (2012), p.12

²³A sheet of white paper on which a large rectangle had been drawn, with few written lines. Above:"This is to show the world that I can paint like Titian". Below:"Only technical details are missing". This was Pauli's comments to the US journalists (he was visiting the States at that time), as a reaction to the german press which had reported, likely not completely correct, on Heisenberg's Göttingen lecture of February 24th, 1958, presenting his new field equation, partially worked out together with Pauli himself, which allegedly provided a unified description of elementary particles (A. Hermann, Heisenberg 1901–1976, 1976 Inter Nations, Bonn–Bad Godesberg).

This very last sentence egregiously summarizes one of the facets of Aage's and Ben's contribution to nuclear physics, namely how to go beyond symmetries and become able to calculate observables which provide an account of the measured values within experimental errors ^{24 25}.

²⁴At a dinner in a downtown Copenhagen steakhouse (situated in Åbenrå street), Aage Bohr remarked to his two young guests, that describing the properties of a many-body system like the atomic nucleus in terms of symmetries, can provide important insight into the structure and dynamics of the system. On the other hand, when one is able to describe the same system in terms of the detailed motion of the particles (nucleons), and of the fields that act upon them is that one obtains, as a rule, a true understanding of the system under consideration.

²⁵Within this context one can mention the unique mechanism to break gauge invariance in nuclei and bind the neutron halo Cooper pair of ${}^7_3\text{Li}_8$ (cf. footnotes 15 and 16).

Appendix B. The spontaneous symmetry breaking restoration paradigm in nuclear structure and reactions

The restoration of translational invariance, and of rotational invariance both in 3D- and in gauge-space, spontaneously broken in nuclei by the privileged position of the finite system (e.g. of its center of mass), by surface deformations, and by superfluidity respectively, leads to zero frequency modes ($\omega \rightarrow 0$) of vanishing restoring force. Thus, divergent zero point fluctuations (ZPF), but finite inertia namely Am , $\hbar^2/2\mathcal{J}$ and $\hbar^2/2\mathcal{J}_p$, where A is the mass number, m the nucleon mass, \mathcal{J} and \mathcal{J}_p the moments of inertia in 3D- and in gauge-space. The resulting elementary modes of excitation are particle motion, and rotations and vibrations. In particular, quadrupole rotations and surface vibrations, and pairing rotations and vibrations.

Because all of the nuclear degrees of freedom are exhausted by the particle degree of freedom, single-particle motion displays a finite overlap with the variety of rotations and vibrations, leading to couplings bilinear in fermions and linear in bosons. In particular, to the particle-vibration coupling ($\Gamma^\dagger(\beta = 0)a_\nu^\dagger a_\nu$, $\Gamma^\dagger(\beta = -2)a_\nu^\dagger a_\nu^\dagger$ and $\Gamma^\dagger(\beta = +2)a_\nu a_\nu$, where the transfer quantum number is $\beta = 0$ for surface modes and $\beta = \pm 2$ for pairing modes, see Fig. 4).

Potential energy privileges fixed position between particles. Fluctuations, classical or quantal, symmetries. Regarding particle motion, such competition is embodied in the quantality parameter

$$q = \frac{\hbar^2}{ma^2} \frac{1}{|v_0|}, \quad (\text{B1})$$

where m is the nucleon mass, v_0 and a the strength and the range of the strong NN-potential ($v_0 = -100$ MeV, $a \approx 1$ fm). The above equation thus provides the ratio between the kinetic energy of confinement, and the potential energy. Because $q \approx 0.4$, nucleons in the nucleus are delocalized, and mean field is a good approximation.

In the case of independent pair motion, pairs of nucleons moving in time reversal states are correlated over distances $\xi \approx \hbar v_F / (2|E_{corr}|) \approx 20$ fm ($v_F/c \approx 0.3$; $E_{corr} \approx -1.5$ MeV in the case of normal nuclei, and equal to the pairing gap $\Delta \approx 1.4$ MeV in the case of superfluid nuclei). The value of the associated generalized quantality parameter

$$q_\xi = \frac{\hbar^2}{2m\xi^2} \frac{1}{|E_{corr}|} \approx 0.03, \quad (\text{B2})$$

testifies to the fact that nuclear Cooper pairs partners are solidly anchored to each other, and thus decoupled from the mean field²⁶. Cooper pair transfer, which mainly proceeds successively, probes pairing correlations equally well than simultaneous transfer.²⁷

The particle-vibration couplings displayed in Fig. 4 clothe the single-particle motion. Thus, a complete characterization of physical single-particle states requires not only single-nucleon transfer but also inelastic and two-particle transfer. This is also true to probe pairing correlations, in keeping with the fact that Cooper pairs are made out of physical particles, bound not only by the $NN^{-1}S_0$ bare potential ($a \approx 1$ fm), but also by the exchange of phonons, of wavelength λ of the order of the nuclear dimensions ($\lambda = 2\pi R/L$ larger or equal than R , R being the nuclear radius and L (2–5) the phonon (vibration) multipolarity). Within this scenario, one can posit that pairing correlation in nuclei receive equally important contributions from short- (bare-) and long- (induced-) interactions.

²⁶This fact has, among other things, important consequences for the moment of inertia \mathcal{J} of e.g. quadrupole rotational bands associated with the restoration of spontaneous symmetry breaking of rotational invariance resulting from deformations in 3D-space (see P. W. Anderson, *More is Different* Sect. 2). In fact, the observed moments of inertia are considerably smaller than the rigid moment of inertia \mathcal{J}_{rig} , typical of independent particle motion ($\mathcal{J} \approx \mathcal{J}_{rig}/2$). On the other hand, the observed values of \mathcal{J} are about a factor of 5 greater than the irrotational moment of inertia \mathcal{J}_{irrot} , typical of a liquid drop of the corresponding shape. This is the scenario of deformed mean field (Nilsson model) in which nucleons form extended Cooper pairs (A. Bohr and B. R. Mottelson, *Nuclear Structure*, vol II (1975) p. 75).

²⁷To assert the contrary will be similar, within the quantum language, to posit that the two slit experiment breaks, when the slits are far away, the photon in two.

Appendix C. The well funneled nuclear structure landscape

Figure 3 displays the root mean square deviations σ between the value of the theoretical predictions and a "complete" set of experimental observations (results) which exhaustively characterize the open-shell superfluid nucleus ^{120}Sn , and involve the island of isotopes $^{118,119,120,121,122}\text{Sn}$, namely (cf. ref. in footnote 14)):

- a) Coulomb excitation and subsequent γ -decay (^{119}Sn)
- b) One-particle transfer reactions ($^{119,121}\text{Sn}$)
- c) Two-particle transfer reactions ($^{118,120,122}\text{Sn}$),

calculated as a function of a number of quantities associated with single-particle and collective motion. One expects that the variety of σ -values do display a minimum for the set of physical quantities determining, through the interweaving of the elementary modes of excitation, the physical states which reproduce the data, regardless of the properties one is looking at or the probe one is using to do it. In other words a well funneled nuclear structure landscape, as is duly observed.

Let us return to "More is different" of Phil Anderson (Sect. 2). I quote: "Three or four or ten (or for that sake $^{120}_{50}\text{Sn}_{70}$, RAB) nucleons whirling about each other do not define ("a condensate" or a "vibrating surface" RAB)... It is only as the nucleus is considered to be a many-body system - in what is often called the $N \rightarrow \infty$ (thermodynamic, RAB) limit²⁸ - that such behaviour is rigorously definable²⁹. We say to ourselves: "A macroscopic body of that shape would have such-and such- a spectrum of rotational and vibrational excitations"(both in 3D- and in gauge-space, and a well funneled behavior with respect to variations of the k -mass, the strength of

²⁸Within this context ($N \rightarrow \infty$), in a number of occasions during November 2015, I discussed with Ben on the structure of the halo of ^{11}Li . In connection with the fact that one was trying to understand a mechanism to break gauge invariance in a situation very far away from $N \rightarrow \infty$, as we were dealing with a single Cooper pair, he asked a number of times, almost to himself, what is large N ? From his smile I could guess that he knew the answer, also very well. To my question of what he meant by that he said: "well, is five or ten a large number, or a million, or for that sake Avogadro's number?". The reader is reminded of the fact that 5-10 is the number of Cooper pairs of a "normal" superfluid nucleus, while 10^6 is the number of Cooper pairs of a low-temperature "normal" metallic superconductor, whose center of mass fall within the extent of a giving pair function (correlation length). In this connection see also P. W. Anderson, More is Different, Sect. 2.

²⁹For example, a swing will have a very simple and perfectly funneled landscape.

the electron–phonon coupling λ (mass enhancement factor, $m_\omega = m(1 + \lambda)$), the Coulomb screening μ , etc., RAB).

When we see such a behaviour in the nuclear case (center diagram of Fig. 3), even not so well defined, and somehow imperfect, we recognize that the physical collective variables CV (Local Elementary Modes of Excitation), defined making use of concepts inspired and worked out to large extent by Aage Bohr and Ben Mottelson, and embodied in the spontaneous symmetry breaking restoration paradigm, provide an accurate (within 10% error) and economic description of the nuclear structure as probed by nuclear reactions. Also the background on which to build upon, to interpret and predict new experiments, in particular concerning exotic nuclei. This is, unarguably, the great achievement that the 1975 Nobel prize in physics recognized.

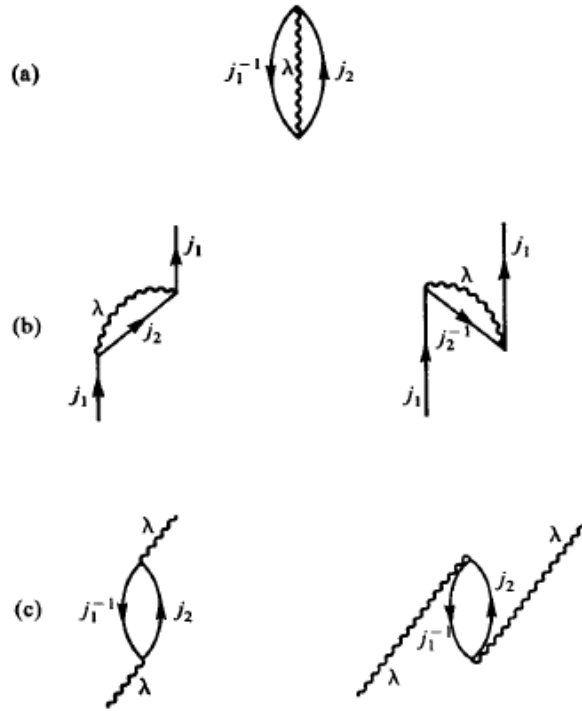


Figure 1: Reproduction of Fig. 6-11 of A. Bohr and B.R. Mottelson, *Nuclear Structure*, Vol. II, Benjamin, Reading (1975). Arrowed lines (j_1, j_2) represent particles (upward) and holes (downward). Wavy lines (λ) vibrations. In (c), the first λ is to be understood as an external field.

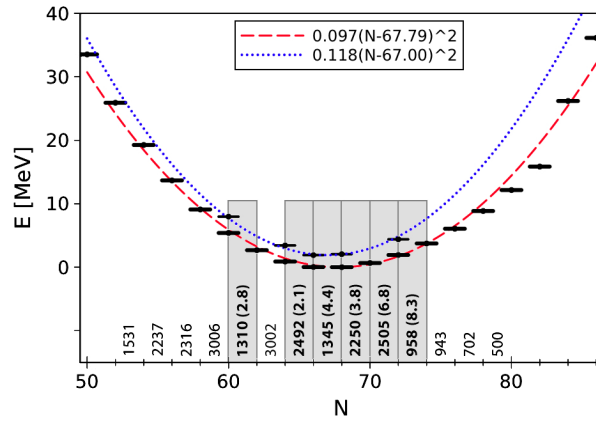
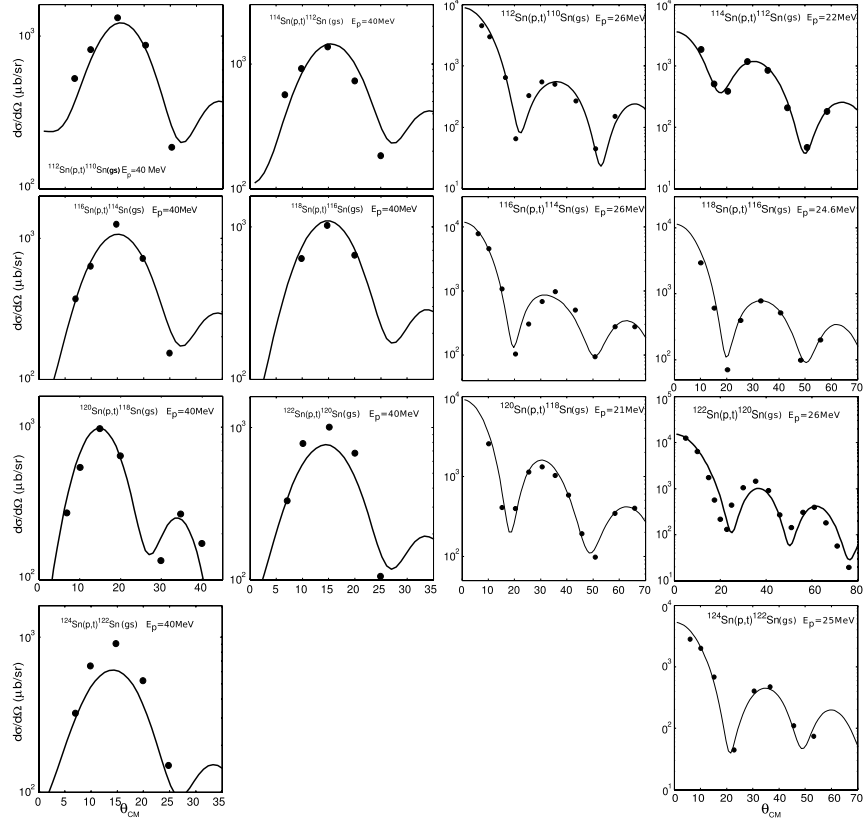


Figure 2: Calculated (continuous curves) absolute differential cross sections associated with the reactions $^A\text{Sn}(p,t)^{A-2}\text{Sn}(\text{gs})$ carried out at 40 (left) and 26 (right) MeV, in comparison with the experimental findings (solid dots). At center bottom, the energies of the ground state, and excited states, pairing rotational bands (for details see footnote 12 and ref. therein).

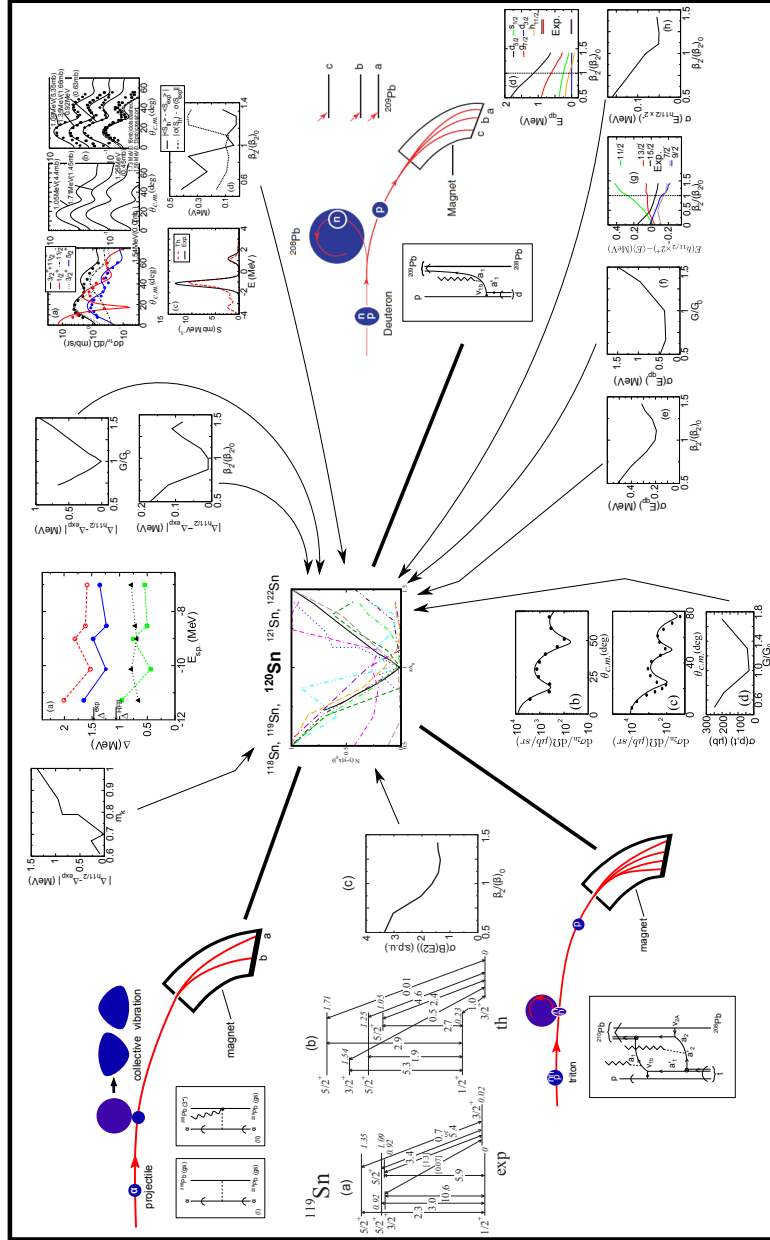


Figure 3: Results of the observations using (α, α') followed by γ -decay, (d, p) , (p, d) , (t, p) and (p, t) reactions, which completely characterize the nucleus ^{120}Sn and involve the island of superfluid nuclei $^{118, 119, 120, 121, 122}\text{Sn}$. By varying the value of a number of inputs (effective k -mass, pairing coupling constant, collectivity of the quadrupole vibration, etc .) one observes (center boxed diagram) that the nuclear landscape is well funneled (for details see ref. in footnote 14).

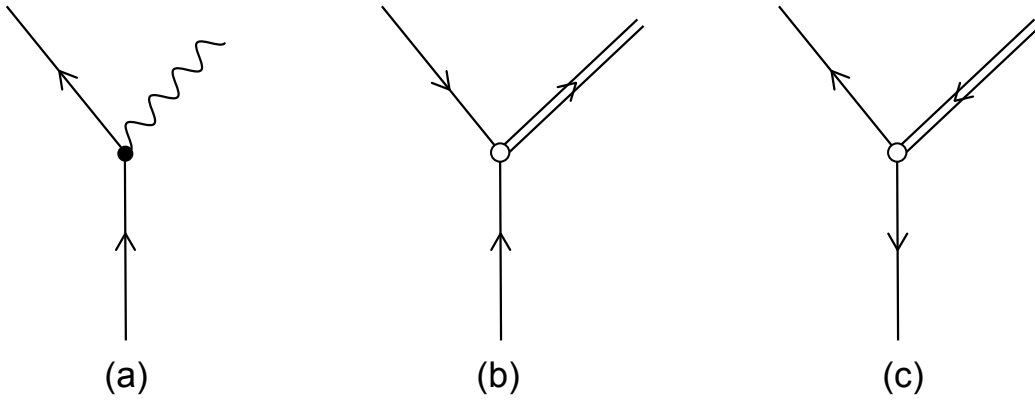


Figure 4: Single line: particle (arrow pointing up); hole (arrow pointing down); surface vibration (wavy line; $\beta = 0$); pair addition (double arrowed line, up; $\beta = +2$); pair removal mode (double arrowed line, down; $\beta = -2$).

NBA History of Science Seminar

40th Anniversary of Aage Bohr and Ben Mottelson's Nobel Prize in physics

This year it is 40 years since the Nobel Prize in physics was awarded to Aage Bohr and Ben Mottelson of the Niels Bohr Institute, together with James Rainwater of Columbia University, New York City.

The Prize was given "for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection". According to fellow physicist Ove Nathan, Bohr and Mottelson's work in the 1950s heralded a second *Golden Age* at the institute comparable in importance to the *Golden Age* of quantum mechanics in the 1920s.



Aage Bohr and Ben Mottelson

On 14 December the Niels Bohr Archive will celebrate the 40th anniversary of the Nobel Prize in the historic Auditorium A. There will be two main lectures:

- Helge Kragh, "**Models of the atomic nucleus: Steps in the historical development, circa 1930–1960**", and
- Ricardo Broglia, "**The 1975 Nobel Prize in Physics: Then and now**".

Historian of science **Helge Kragh** has studied the history of 20th century physics extensively and will provide the historical background. Italy-based Argentinian physicist **Ricardo Broglia** worked closely with Bohr and Mottelson and was at the institute when the Prize was awarded. He will provide reminiscences from that time as well as discuss the relevance of Bohr and Mottelson's work to this day.

Time: 14 December 2015, 14:15-16:30

Place: Aud. A, Niels Bohr Institute, Blegdamsvej 17, Copenhagen

Organizer: Niels Bohr Archive